Review of neutrino cross-section on free and bound nuclei

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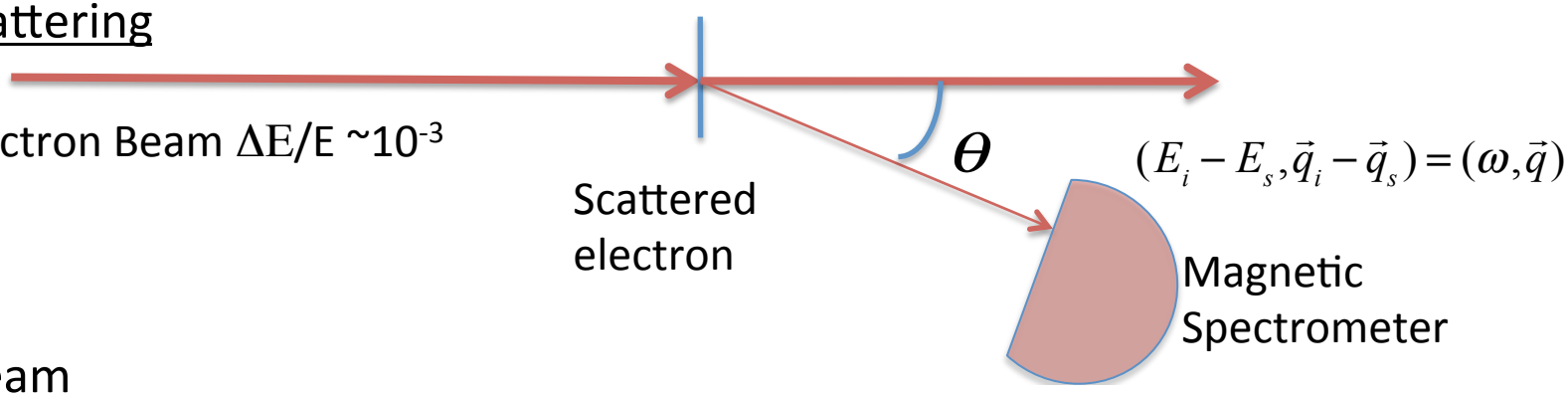
Outline

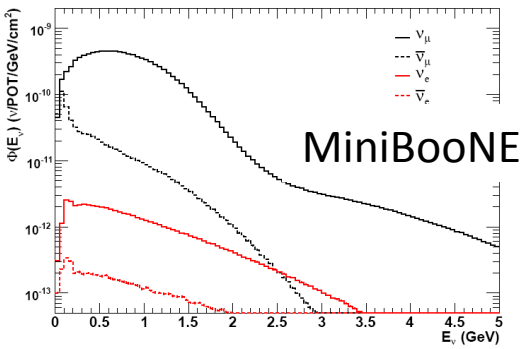
- electron scattering:
  - some theory background - tools needed
  - electron scattering data: what can we do with them ?
  - new ideas beyond the Relativistic Fermi Gas Model
  - Meson Exchange Current
- neutrino cross-sections:
  - state of the art measurements (C, Ar, …)

Electron Scattering vs ν cross-sections

Electron Scattering



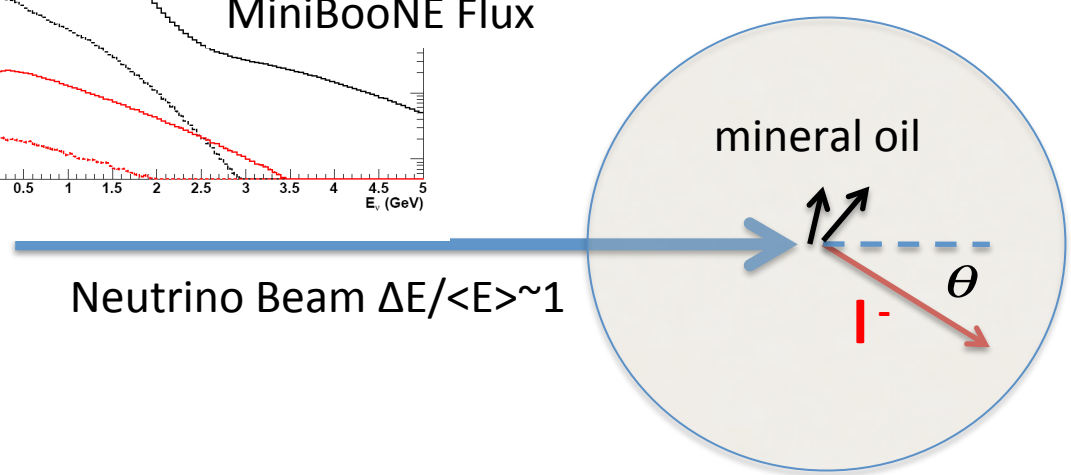
Neutrino beam

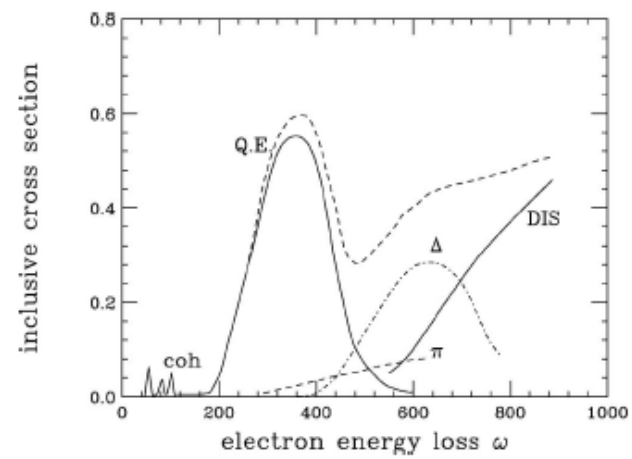


MiniBooNE Flux

$(E_i - E_s, \vec{q}_i - \vec{q}_s) = (\omega, \vec{q})$

MiniBooNE Detector





Don't know E_ν !

What's ω ???

What's q ???

Bottom line: in neutrino experiments the energy and momentum are not precisely known, several assumptions are needed

Little bit of theory

- ★ Double differential electron-nucleus cross section

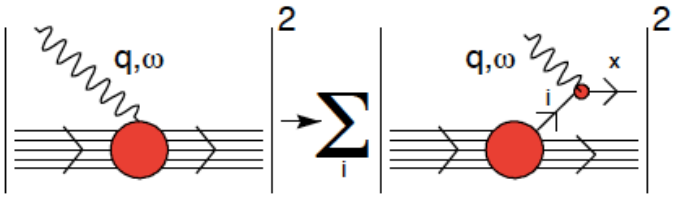
$$\frac{d\sigma_{eA}}{d\Omega_{e'}dE_{e'}} = \frac{\alpha^2}{Q^4}\frac{E'_e}{E_e}L_{\mu\nu}W_A^{\mu\nu}$$

  - ▹ $L_{\mu\nu}$ is fully specified by the *measured* electron kinematical variables
  - ▹ the determination of the target response tensor

$$W_A^{\mu\nu} = \sum_X \langle 0|J_A{}^\mu|X\rangle\langle X|J_A{}^\nu|0\rangle\delta^{(4)}(P_0 + k_e - P_n - k_{e'})$$

  requires a *consistent* description of the target internal dynamics and electromagnetic current, unavoidably implying approximations

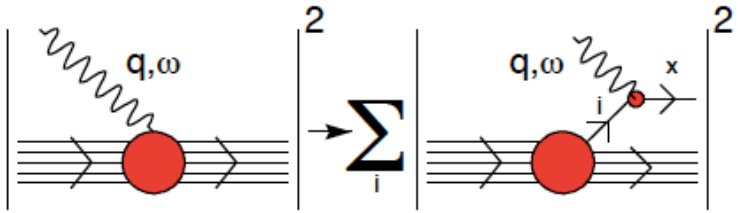
- ★ Impulse approximation (IA): at large momentum transfer electron-nucleus scattering reduces to the incoherent sum of scattering processes involving individual nucleon



$$J_A{}^\mu = \sum_i j_i{}^\mu \quad , \quad |X\rangle \to |x, \mathbf{p}_x\rangle \otimes |\mathcal{R}, \mathbf{p}_\mathcal{R}\rangle \, .$$

Little bit of theory (cont'd)

★ The IA amounts to the replacement



$$J_A{}^\mu = \sum_i j_i{}^\mu \quad , \quad |X\rangle \to |x, \mathbf{p}_x\rangle \otimes |\mathcal{R}, \mathbf{p}_\mathcal{R}\rangle \, .$$

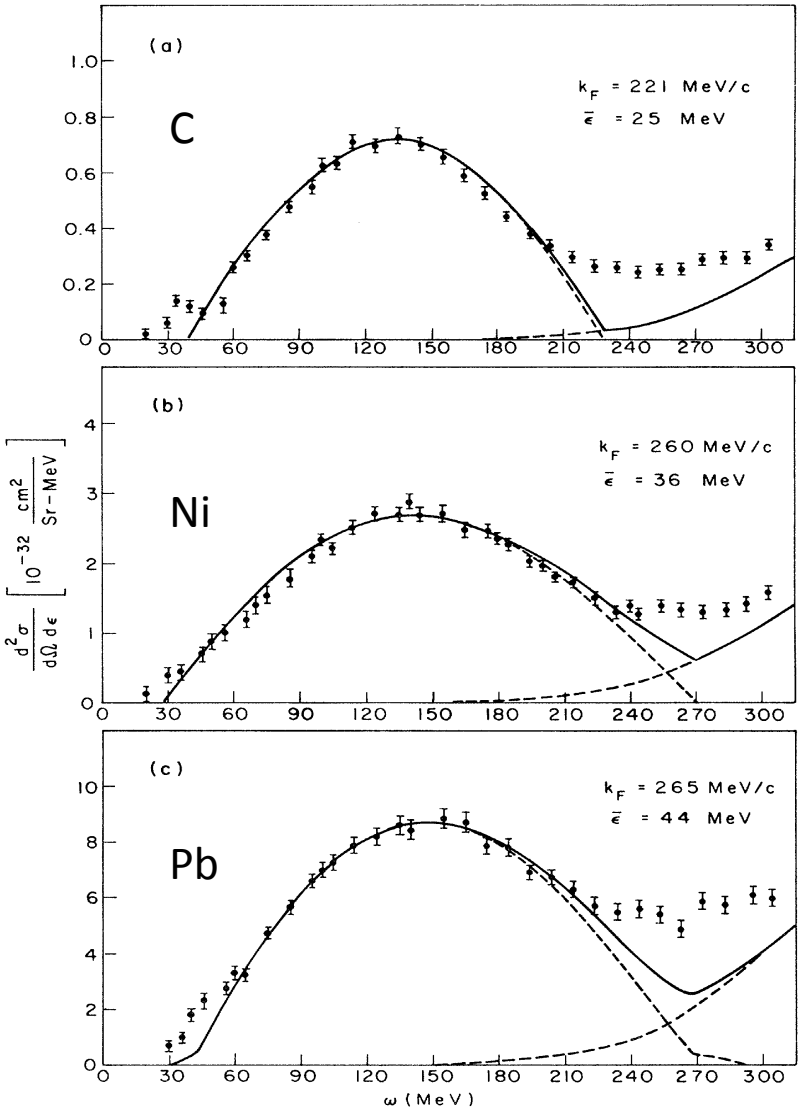
★ Nuclear dynamics and electromagnetic interactions are *decoupled*

$$d\sigma_A = \int d^3k dE \, d\sigma_N \, P(\mathbf{k}, E)$$

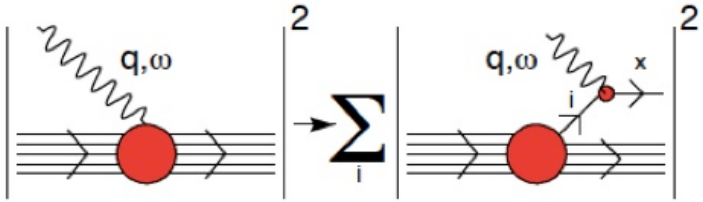
- The electron-nucleon cross section $d\sigma_N$ can be extracted from electron-proton and electron-deuteron scattering data
- The spectral function $P(\mathbf{k}, E)$, momentum *and* energy distribution of the knocked out nucleon, can be obtained from *ab initio* many-body calculations

Quasi-Elastic Scattering in Nuclear Physics originated from Electron-Nucleus Scattering

Moniz et al PRL 1971



Impulse Approximation



Simple Fermi Gas: 2 parameter , S_E, p_F

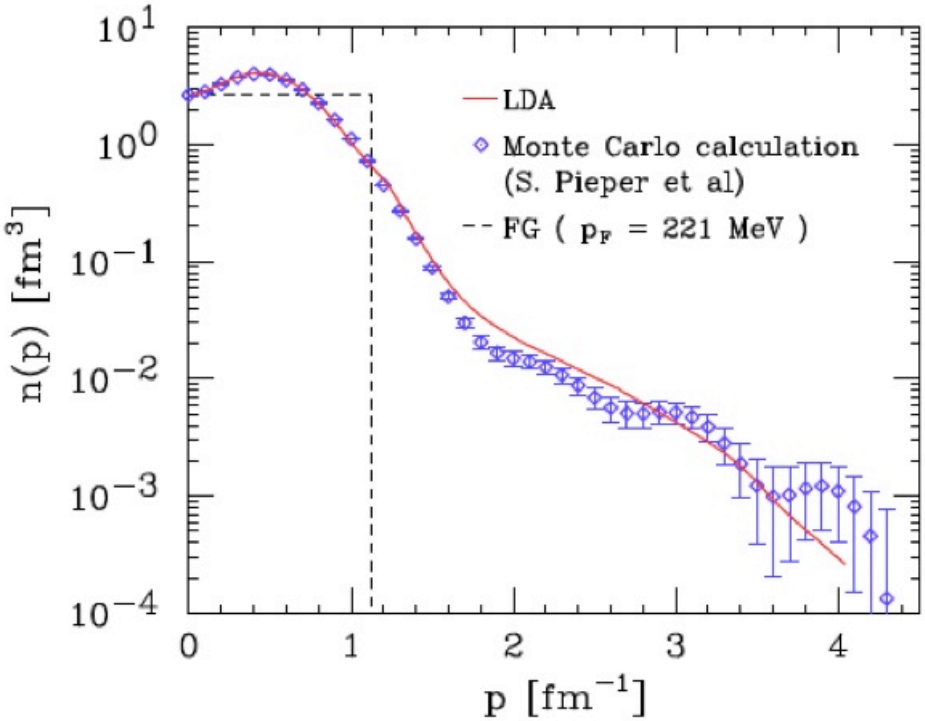
$$(E,\vec{p})-(E',\vec{p}')=(\omega,\vec{q}),\quad Q^2=\vec{q}^{\,2}-\omega^2$$

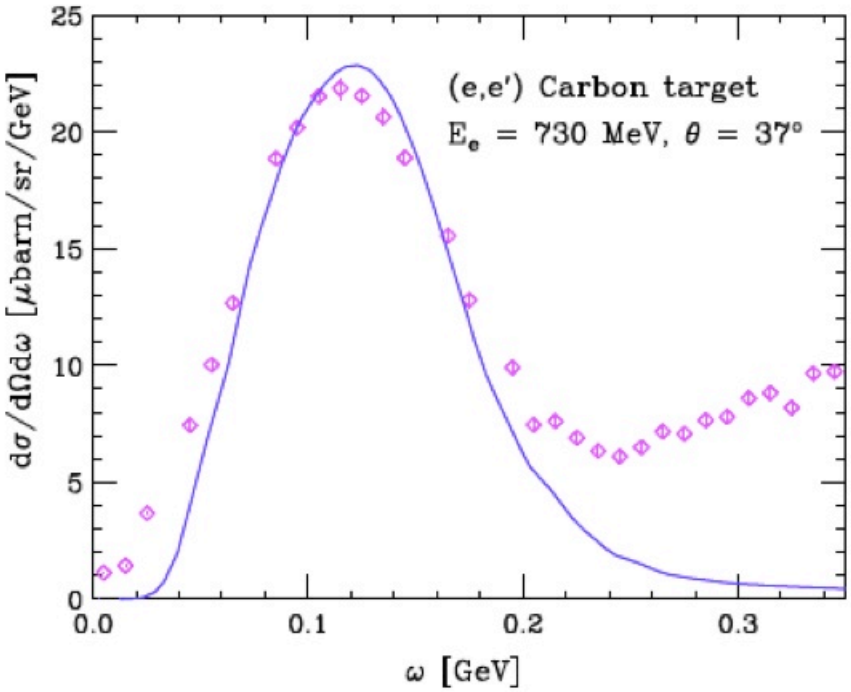
$$\omega=\frac{Q^2}{2m}+S_E$$

$$\Delta\omega=\frac{(\vec{q}+\vec{p}_F)^2}{2m}$$

$V_N=4\pi/3(1.2)^3A\ 10^{-39}cm^3$ $p_F=250MeV/c$

Fermi Gas Model vs Spectral Function (cont'd)



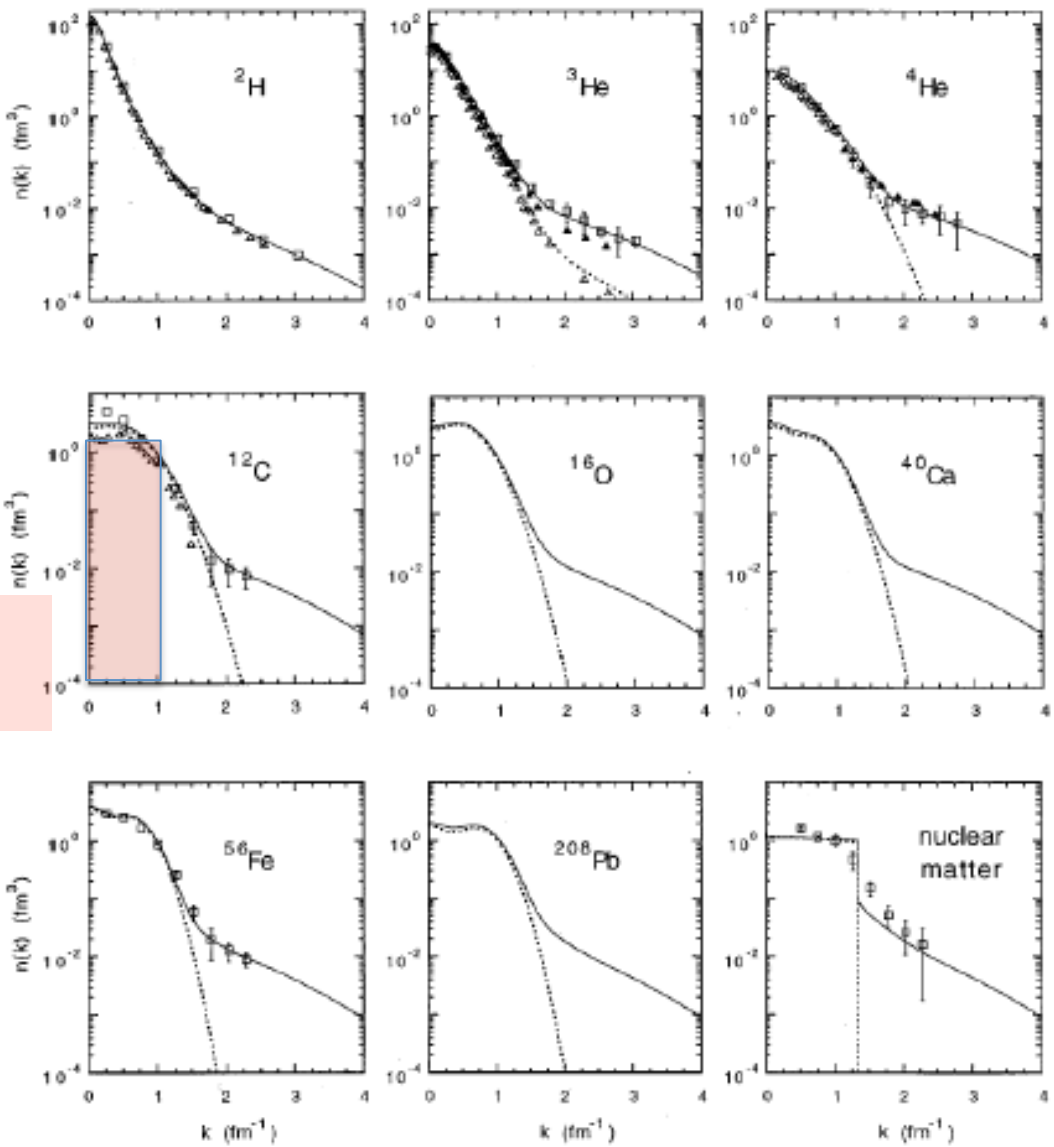


- ★ FG model: $P_h(\mathbf{k}, E) \propto \theta(k_F - |\mathbf{k}|)\, \delta(E - \sqrt{|\mathbf{k}|^2 + m^2} + \epsilon)$
- ★ shell model states account for $\sim 80\%$ of the strenght
- ★ the remaining $\sim 20\%$, arising from NN correlations, is located at high momentum *and* large removal energy ($\mathbf{k} \gg k_F, E \gg \epsilon$)

Momentum Distribution

arXiv:1104.1196v3 [nucl-ex] 26 Mar 2012

n(k)(fm^3)



Fermi Gas

If the two-body NN interaction is responsible for the high-momentum tail of the nuclear momentum distribution, then one expects the shape of the distribution beyond the Fermi momentum to be essentially the same.

The momentum distributions are similar for k > 1.5fm^{-1}

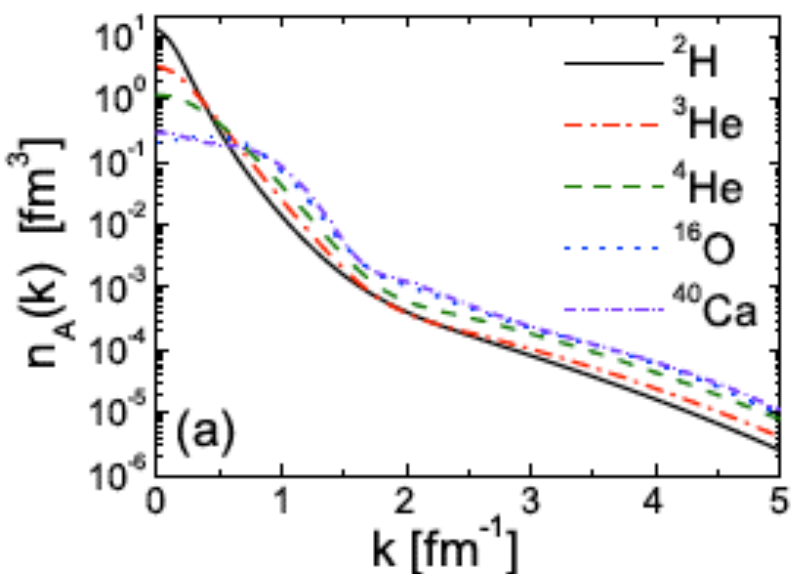
Momentum Distribution cont'd

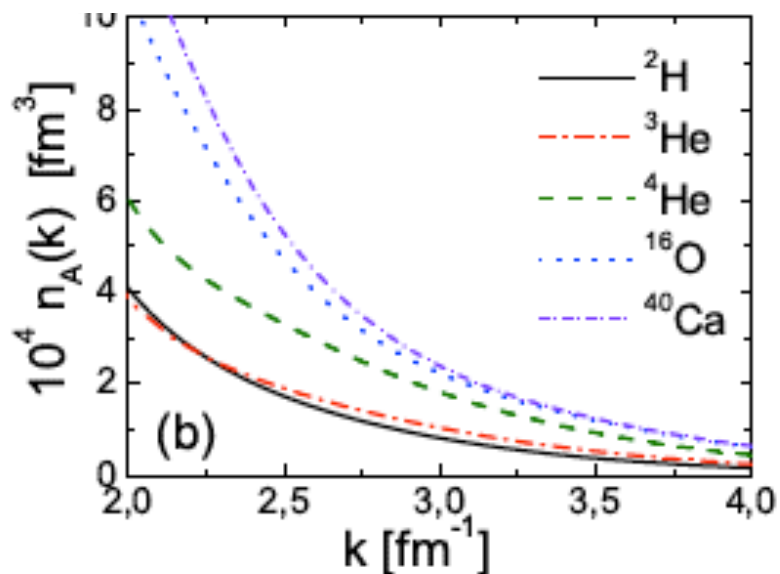
Model dependent – non unique n_0

$$\mathcal{P}^{N_1}_{0(1)}(k_1^{\pm}) = 4\pi \int_{k_1^-}^{k_1^+} n^{N_1}_{0(1)}(\boldsymbol{k}_1) k_1^2 \, d\, k_1$$

arXiv 1211.0134, Alvioli, degli Atti, et al.

	^2H	^{3}He(n)	^{3}He(p)		^{4}He		^{16}O		^{40}Ca	
k_1^- [fm^{-1}]	$\mathcal{P}$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_0$	$\mathcal{P}_1$
0.00	1.000	0.999	0.677	0.323	0.84621	0.15285	0.79999	0.20016	0.80	0.19321
0.50	0.3078	0.568	0.277	0.201	0.53643	0.14032	0.66972	0.19635	0.69997	0.18301
1.00	0.081	0.163	0.038	0.0723	0.10479	0.1045	0.17588	0.14794	0.24706	0.13771
1.50	0.0366	0.067	0.0049	0.036	0.0079	0.0791	0.00792	0.09417	0.01022	0.10143
2.00	0.0221	0.041	0.0015	0.024	$6.9512\,10^{-4}$	0.06156	$5.9\,10^{-5}$	0.06344	$3.28\,10^{-4}$	0.07124

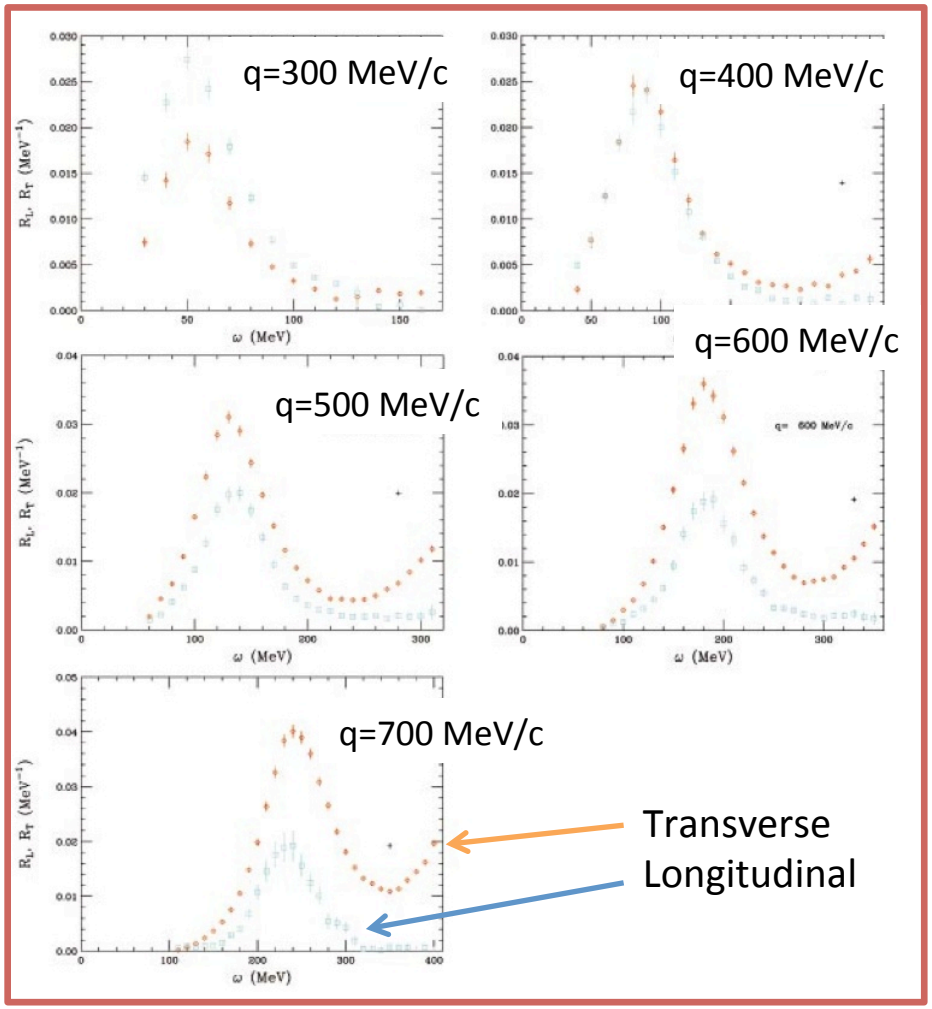


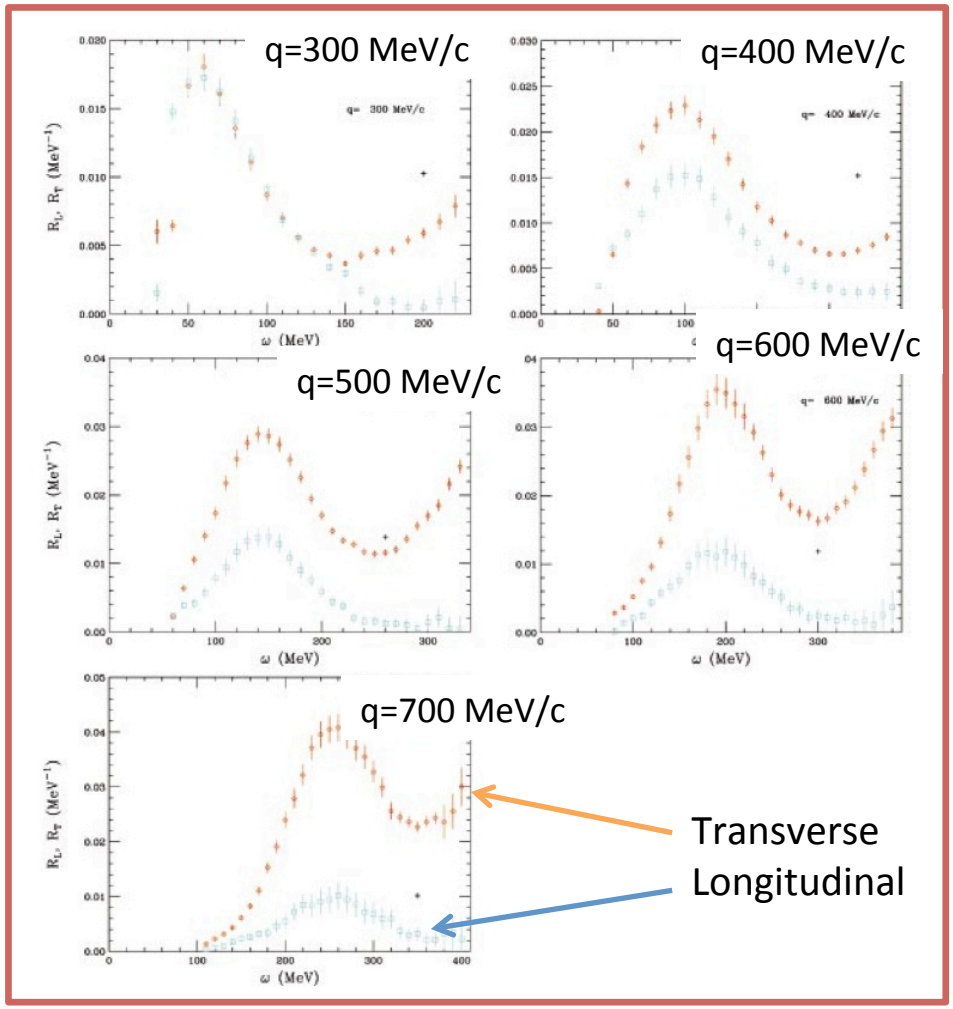


Transverse and longitudinal response functions

Carlson et al. Phys. Rev. C65 024002 (2002)

Response Functions from ^{3}He and ^{4}He from (e,e') Quasi-elastic Scattering



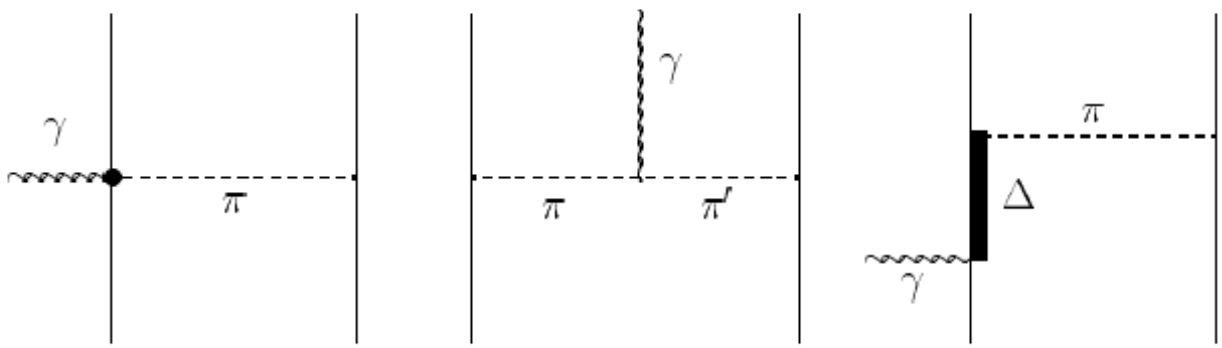


MEC - Meson Exchange Current

- The nuclear electromagnetic current involves two-nucleon contributions, arising from nucleon-nucleon interactions and nucleon excitations

$$J_A^\mu = \sum_{i=1}^{A} j_1^\mu(i) + \sum_{j>1=1}^{A} j_2^\mu(i,j)$$

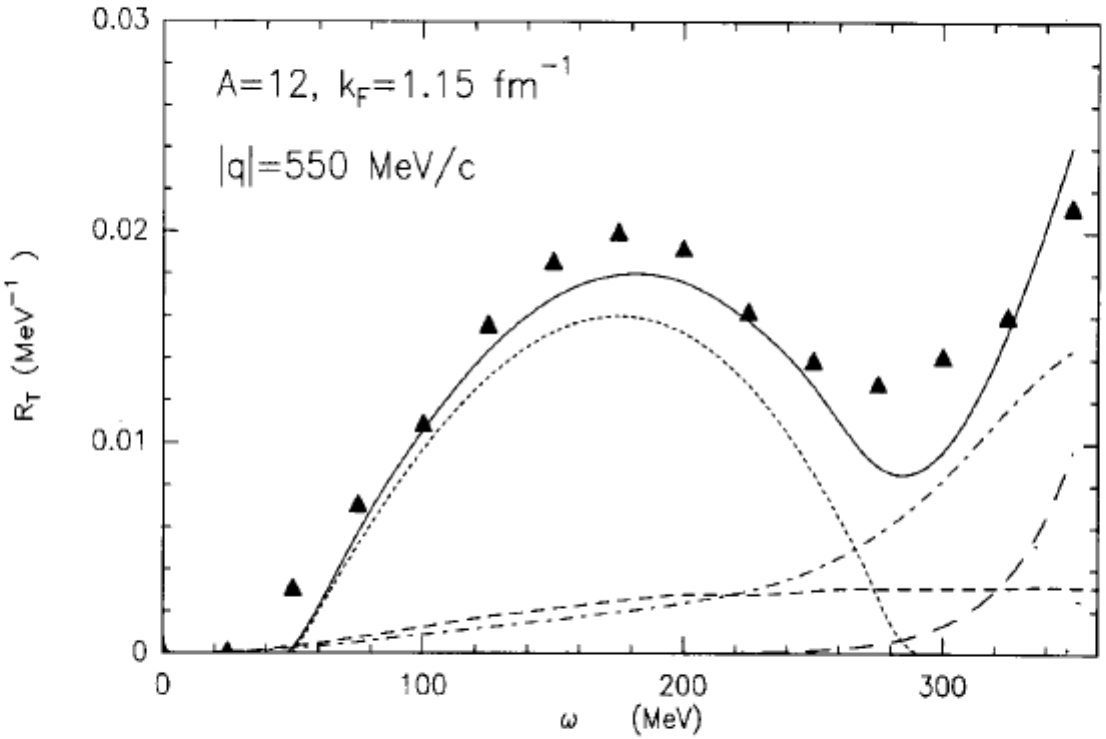
- Meson exchange current (MEC) arising from processes involving pions



- Note: coupling to MEC *does not* lead to the appearance of pions in the final state

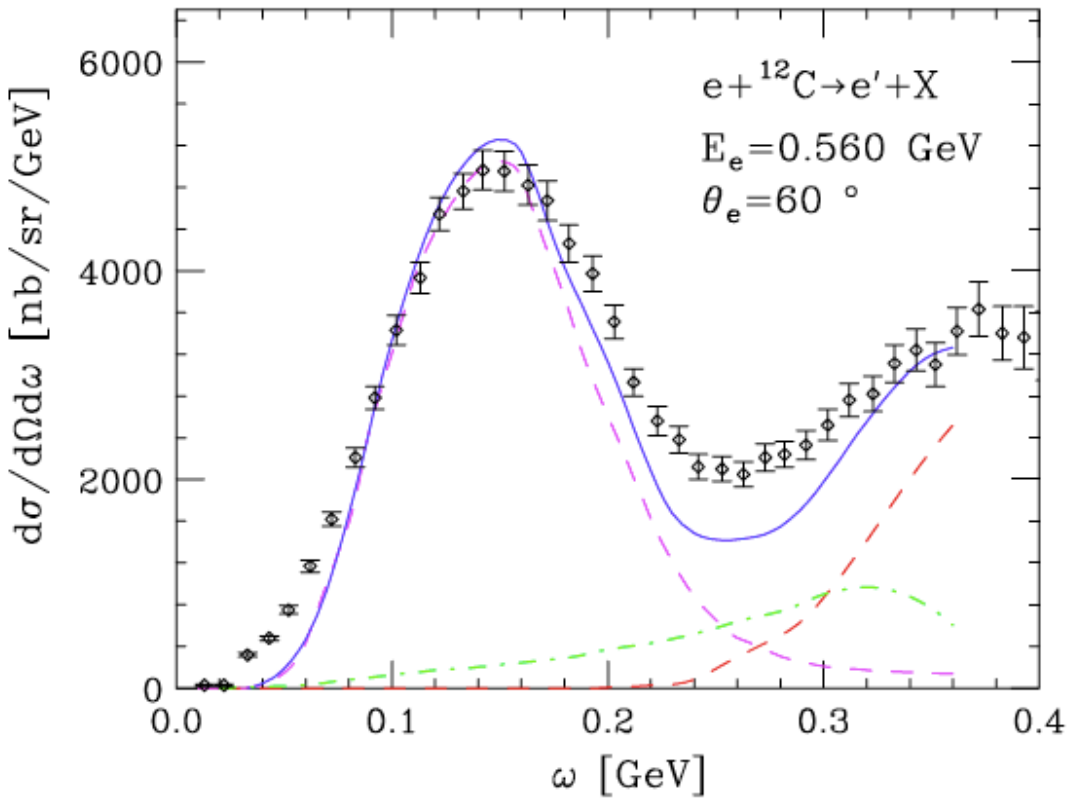
Meson Exchange Current effect in C

- Calculations by M.J. Dekker *et al* (Fermi gas model, AD 1991)



- Results of theoretical calculations based on more realistic models of nuclear dynamics suggest that estimates based on the Fermi gas model should be ragarded as *lower bounds* to the MEC contribution

MEC on Carbon (cont'd)



- ★ Adding the MEC contribution estimated by Dekket *et al* to the IA results obtained from state-of-the-art spectral functions and parametrizations of the nucleon structure functions sugnificantly improves the agreement between theory and data.

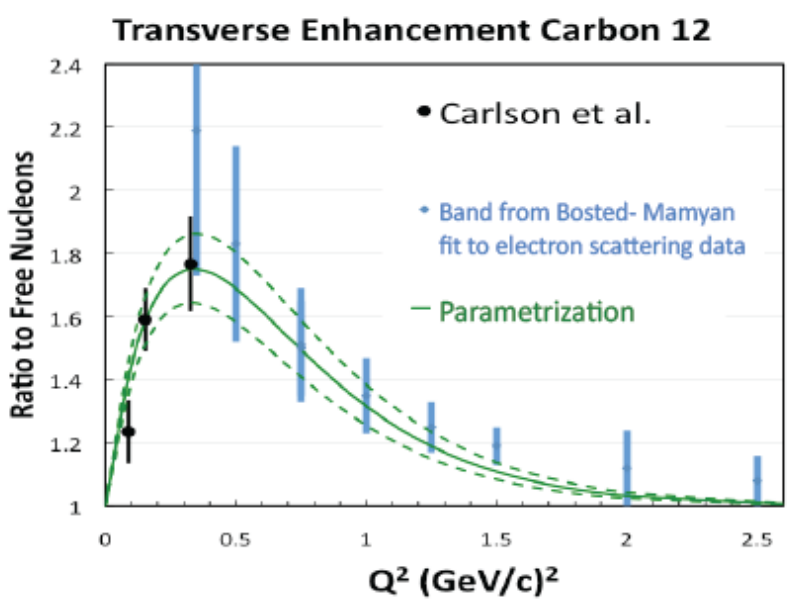
Alternative approach:
enhance the transverse vector response of the nuclear effect

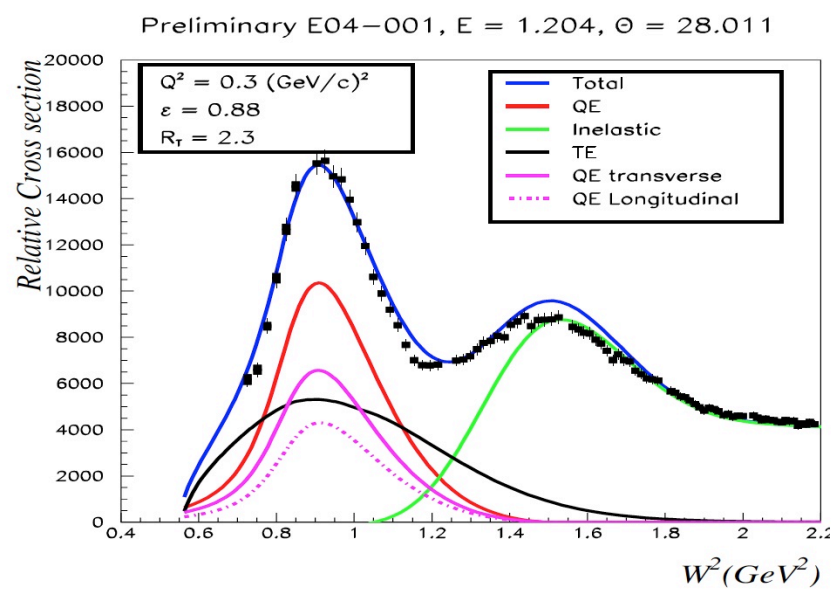
Bodek et al: Eur. Phys. J. **C71** (2011) 1726 assigned the enhancement to the transverse vector response. In impulse approximation,

$$\sigma_{\nu,(\bar{\nu})} \sim V_L^2 + V_T^2 + A_T^2 + (-)2A_T V_T$$

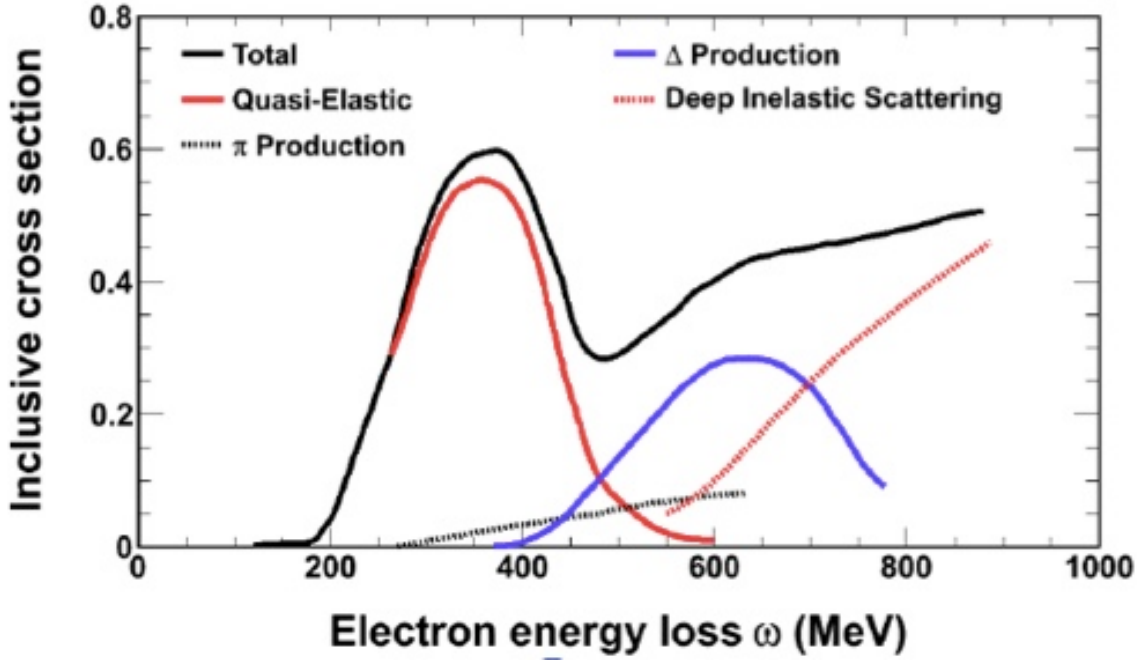
Without addressing any dynamics Bodek et al. create the enhancement via increasing V_T as a function of Q^2, using $Q^2=4E_\nu E_l sin^2\theta/2$

$$R_T^V = 1 + 6.0Q^2 e^{-\frac{Q^2}{.34}}$$





Moving to neutrino cross-sections



MiniBooNE CCQE and the M_A puzzle

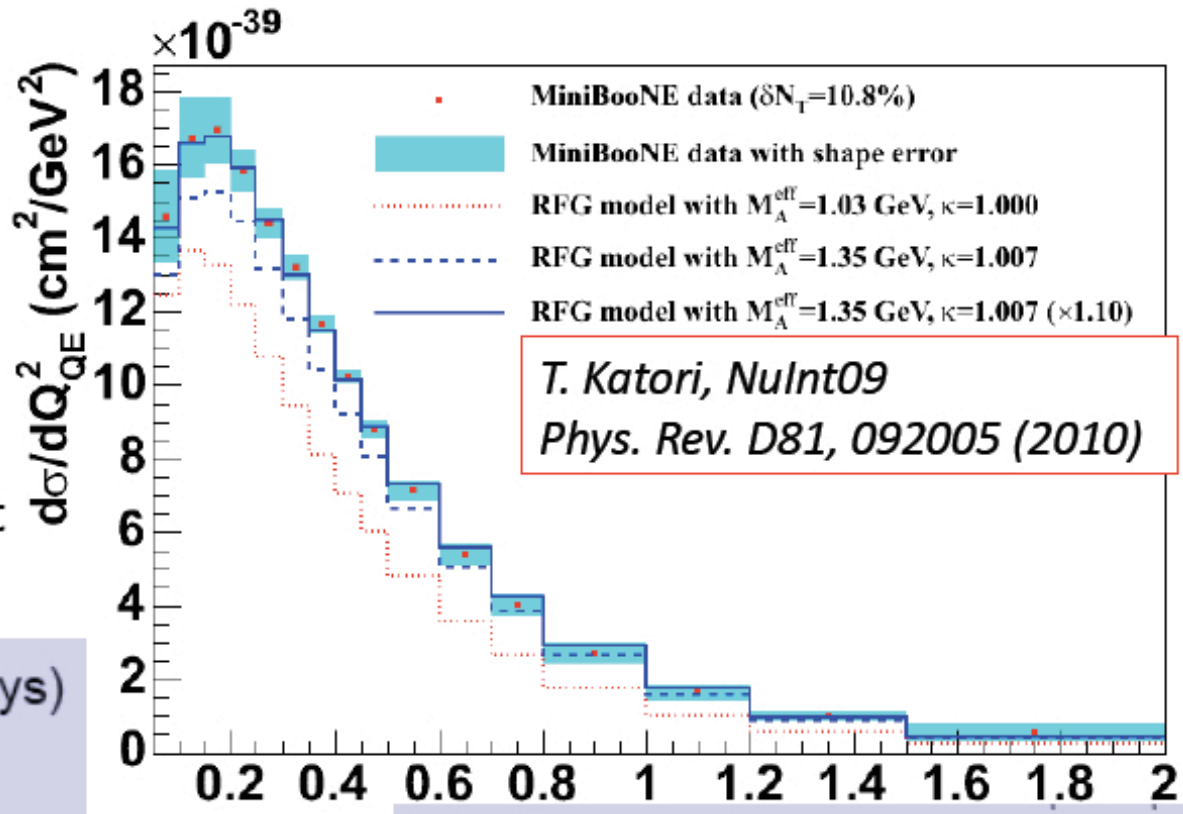
800 ton, spherical mineral oil Cherenkov detector (E_ν~1 GeV, carbon target)

- Muon identified with decay electron, no direct selection on proton
  - Purity: 75.8%, efficiency: 26.5%
- CC1π background are constrained based on CC1π selected event sample
- NUANCE generator

Data favors a higher value of M_A^{eff} as compared to earlier bubble chamber data, consistent with K2K results

Shape fit produces agreement in muon KE and angle important for oscillation analysis

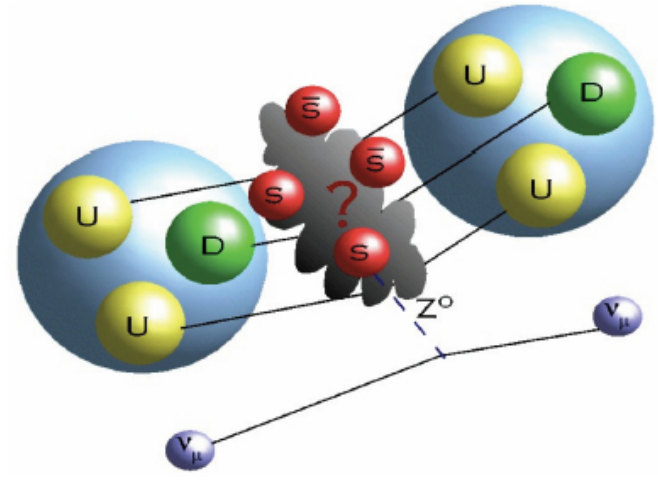
M_A^{eff} = 1.35 ± 0.17 GeV (stat+sys)
$\kappa = 1.007^{+0.007}_{-\infty}$ (stat+sys)
χ^2/ndf = 47.0/38



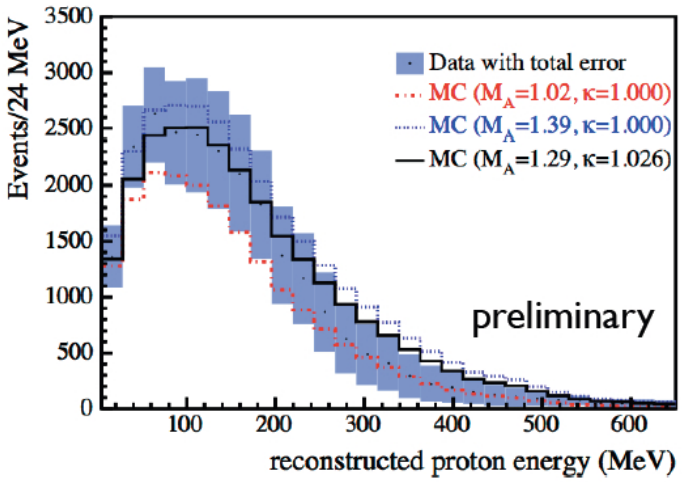
T. Katori, NuInt09
Phys. Rev. D81, 092005 (2010)

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

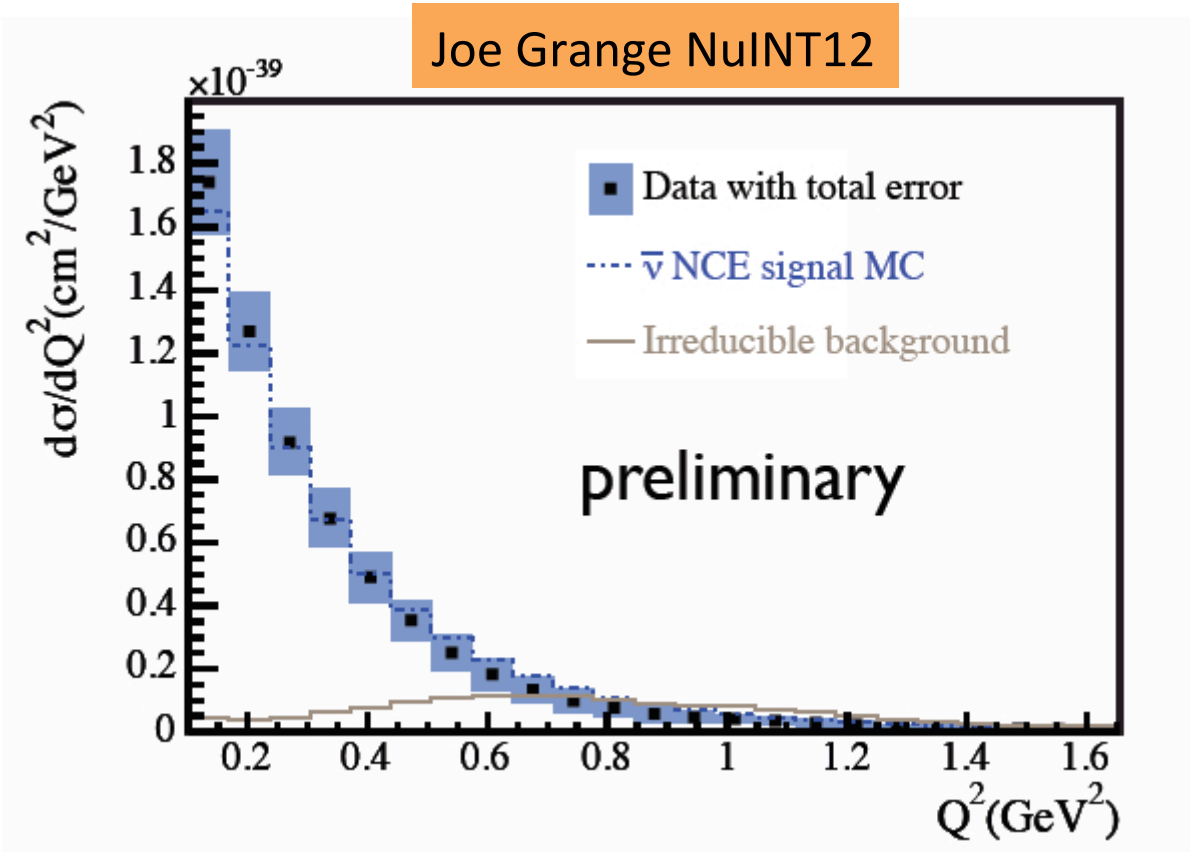
MiniBooNE Neutral Current Elastic



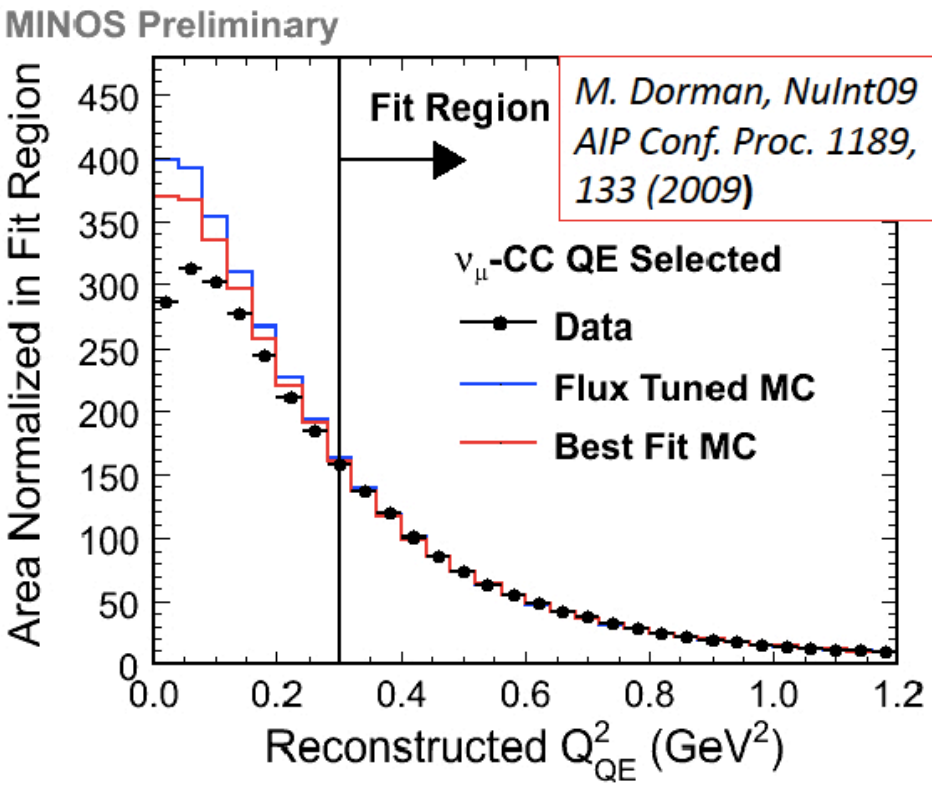
Offer sensitivity to the hadronic side of elastic interaction



Joe Grange NuINT12



MINOS CCQE and M_A

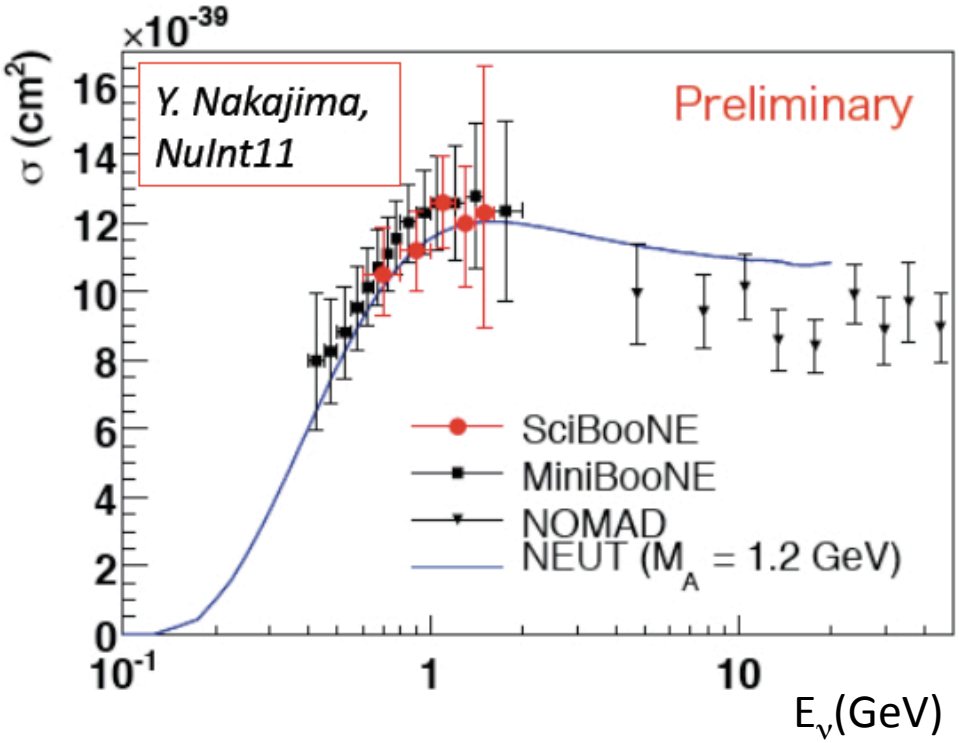


$$M_A^{eff.} = 1.26^{+0.12+0.08}_{-0.10-0.12}$$

Scintillator-steel sandwich detector (E_ν ~2.5 GeV, iron target)

- Select muon candidate and uses hadronic shower energy to reject DIS, RES
  - Purity: 61%, efficiency: 53%
- Flux tuned from data in different beam configurations
- NEUGEN generator

SciBooNE CCQE and M_A



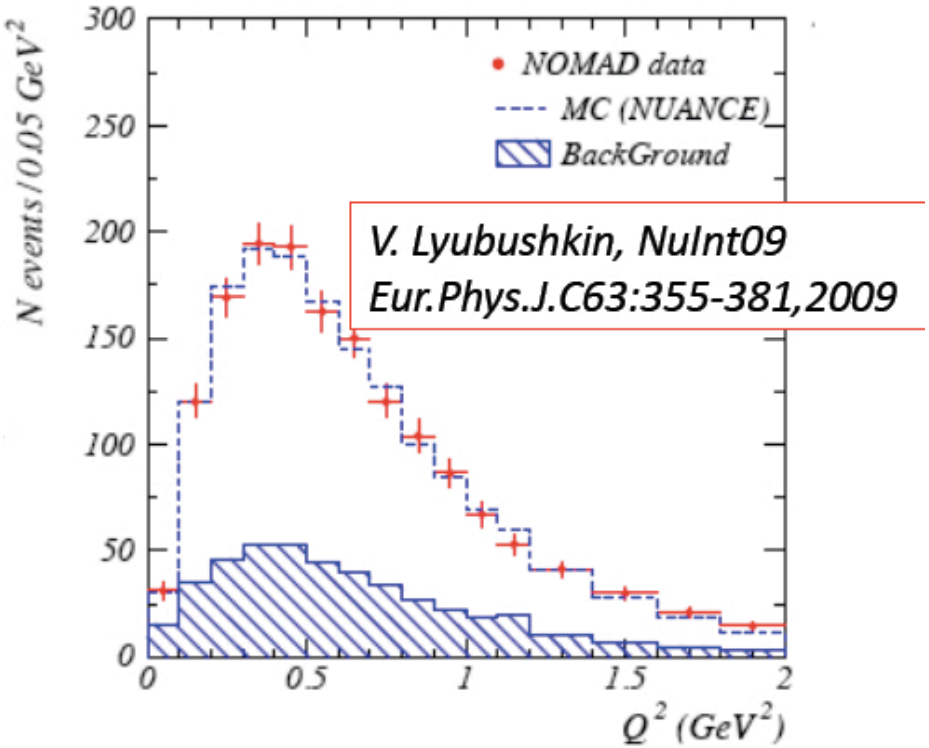
$$M_A^{eff.} = 1.2$$

Value consistent with what measured in the K2K experiment with the same detector but different beam

Scintillator sandwich detector with electron calorimeter, muon range detectors (E_ν ~1 GeV, carbon target)

- "1 track" (muon only, ~13.5k) and "2 track" (muon, proton, ~3k events) used
  - Purity: 66.2% (1 track), 68.5% (2 track)
  - "2 track" (mu+π, ~1.5k) also included to constrain backgrounds
- NEUT generator

NOMAD CCQE and M_A

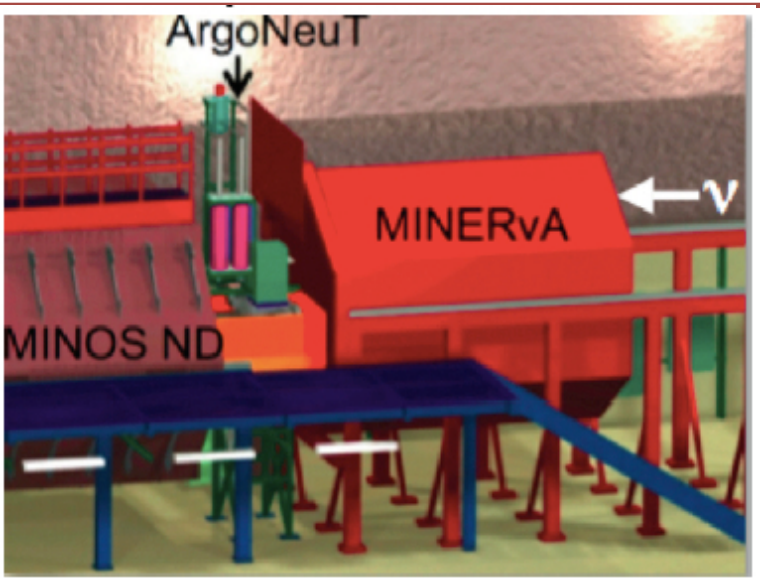


$$M_A^{eff.} = 1.05 \pm 0.02 \pm 0.06$$

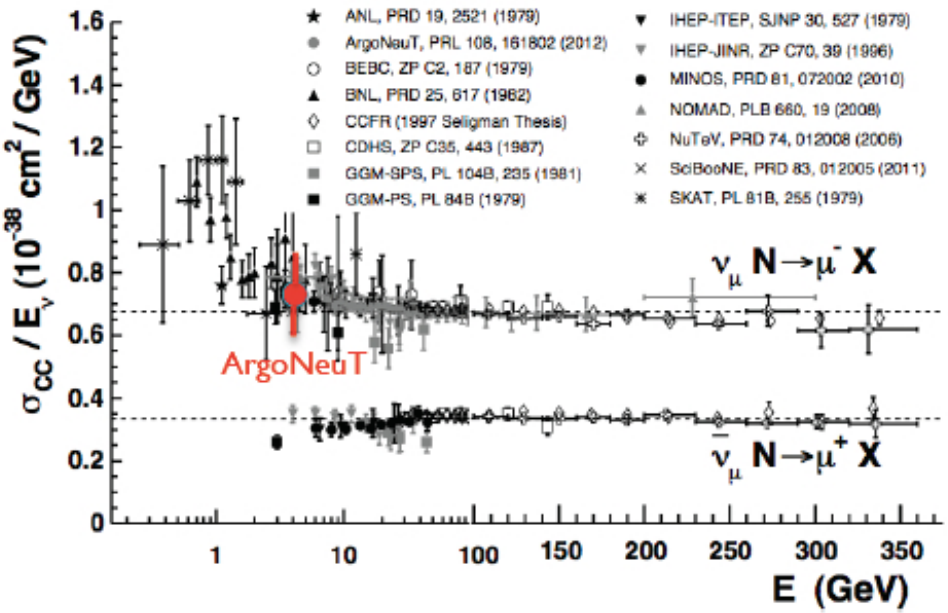
Drift chambers with hadronic calorimeters and muon detectors situated in magnetic field (E_ν ~24 GeV, carbon target)

- "1 track" (muon only, ~10k) and "2 track" (muon, proton,~3.5k) samples
  - Purity: 50.3%, efficiency:34.6%
- Flux normalized based on inverse muon decay (~400 events)
- Smith-Moniz MC with intra-nuclear cascade model (DPMJET based)

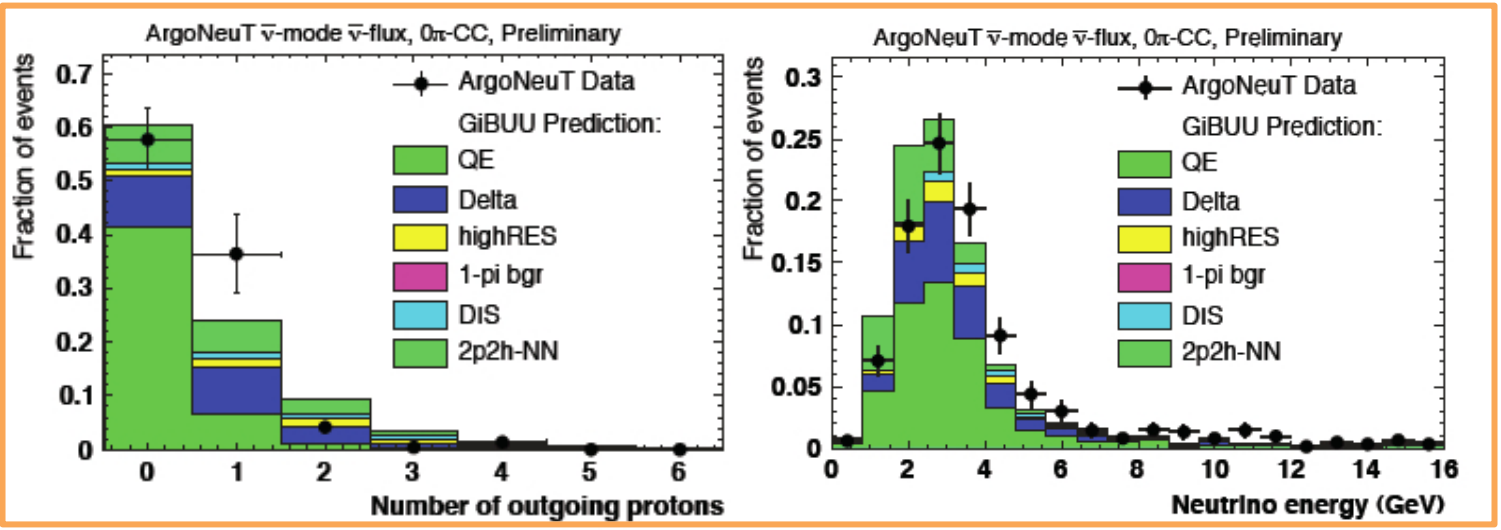
ArgoNeut



ν mode - 8.5e18 POT – PRL 108 (2012)

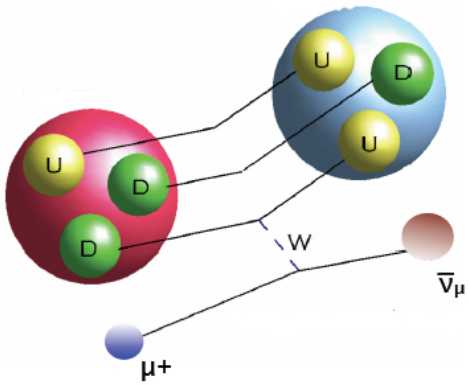


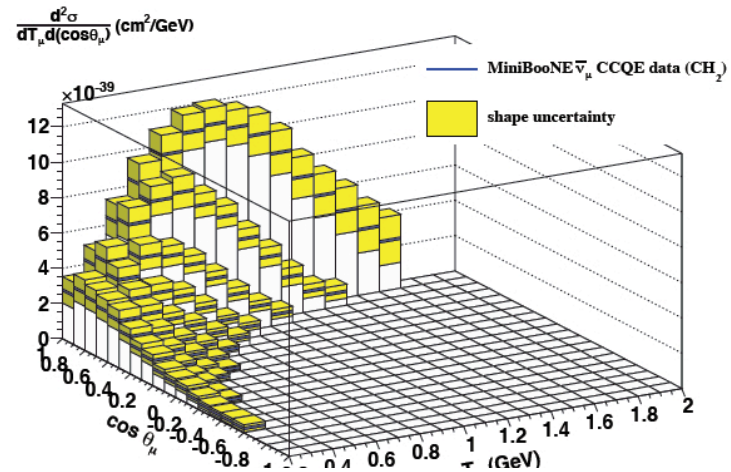
Anti-ν data available as well

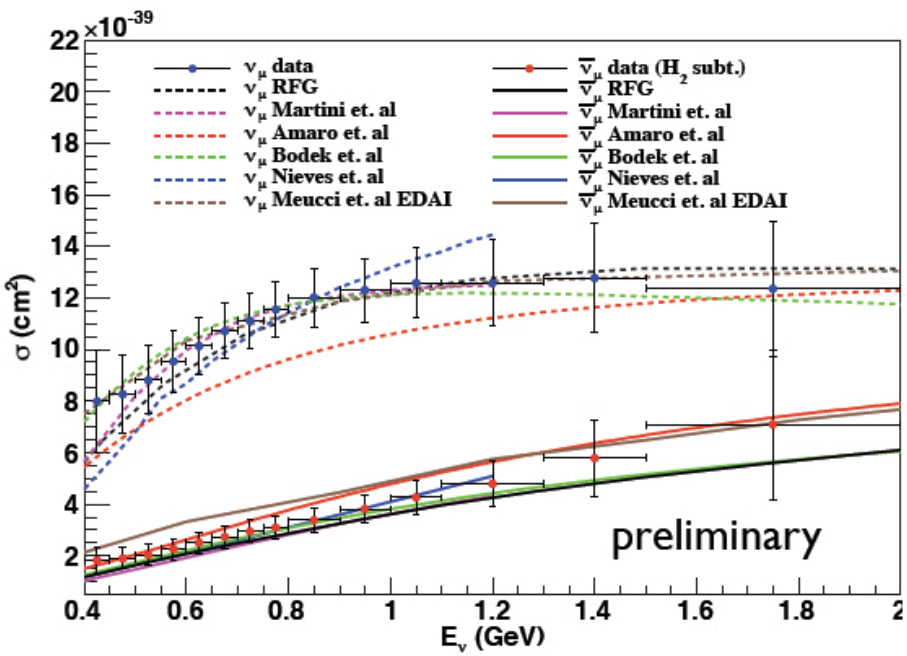


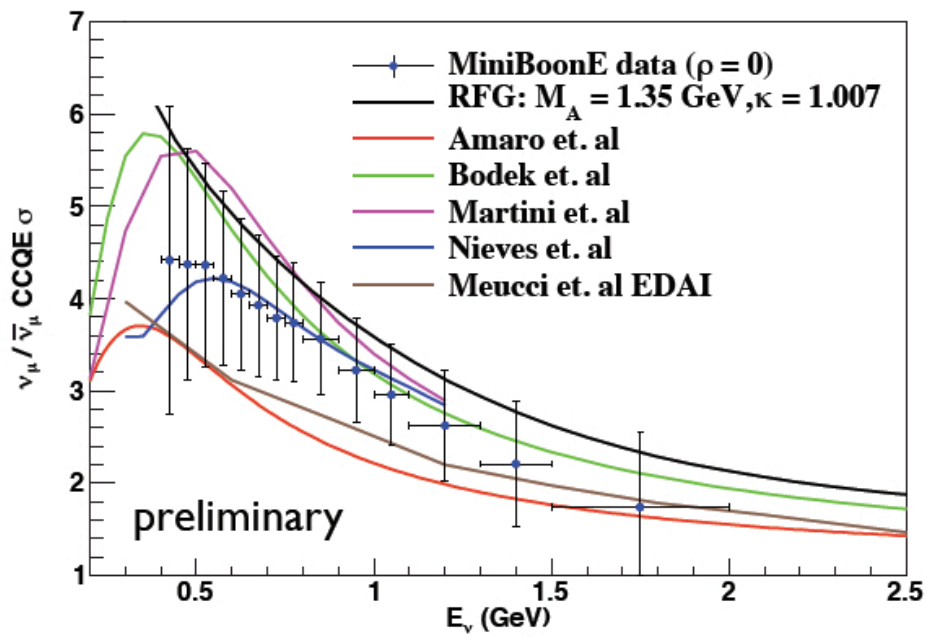
See Ornella's talk

MiniBooNE anti-ν CCQE



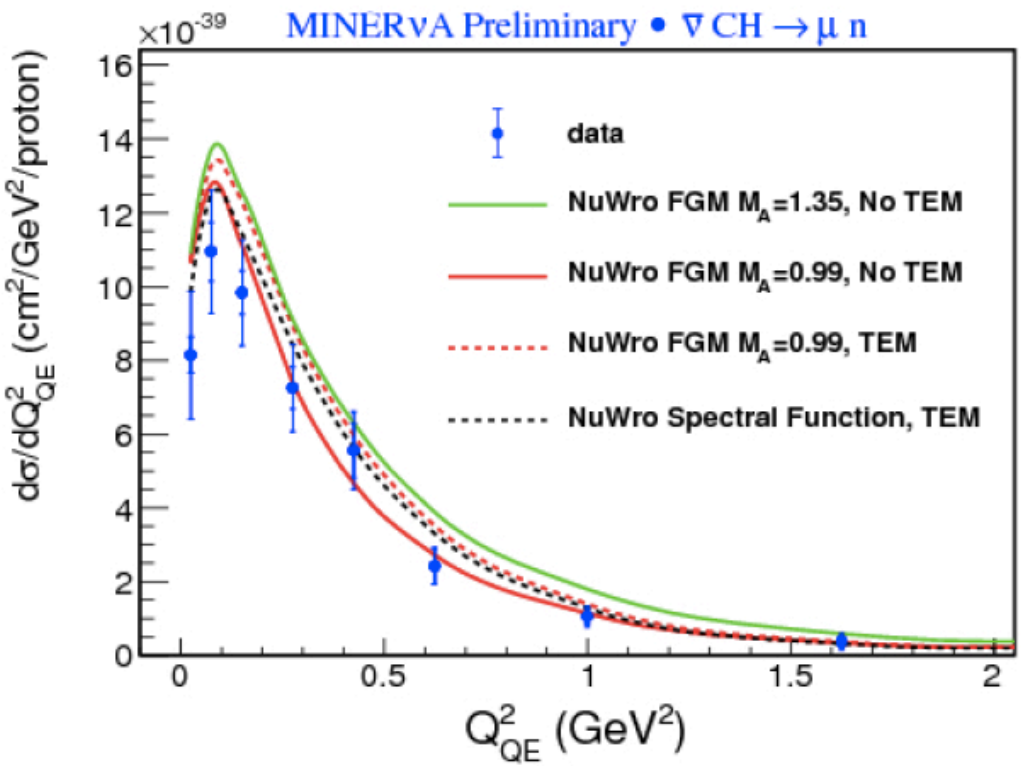






Minerva anti-ν CCQE

- Scintillator sandwich detector with electron calorimeters, MINOS muon range detector
- E_ν ~2.5 GeV, multiple targets (CH shown)
- GENIE generator



First measurements of CCQE on multiple targets will come this year !

Summary

Many experimental results – some of those very controversial: theorists and experimentalists need to work together. Future should be a collaboration like CTEQ.

We need to uniform our MC generator and include as many models as possible inside it, then the experiment will compare with their data and determine the model that best fit the data.

Lesson learned from the past should not be forgotten: electron scattering data are available and every new model should not only fit the new data but also the old ones. We know a lot already and we cannot ignore it. We need coherent treatment of different effects.

Summary cont'd

Meson exchange current effects need to be included in the MC generator/s and try to fit the data, but the kinematic should be right – spectral functions seem the only way to go.

Lack of electron scattering data on Argon – an idea would be to take some electron scattering data with an argon target. (Ingo Sick - JLab)

Thank you